OBSERVATIONS ON DIFFERENCES BETWEEN THE ENERGY DETERMINED USING AN INSTRUMENTED STRIKER AND FROM A DIAL/ENCODER

M. P. Manahan, Sr. [1], R. B. Stonesifer[2], T. A. Siewert[3], C. N. McCowan[3], and D. P. Vigliotti[3]
[1] MPM Technologies, Inc., 2161 Sandy Drive, State College, PA 16803 USA
[2] Computational Mechanics, Inc., 1430 Steele Hollow Road, Julian, PA 16844 USA
[3] National Institute for Standards and Technology, 325 Broadway, Boulder, CO 80305 USA

ABSTRACT

Instrumented striker systems, dial indicators, and optical encoders are widely used for measurement of absorbed energy in both conventional and miniature Charpy tests. It has been observed that the total absorbed energy measured using these technologies, while generally in good agreement, sometimes differs by a significant amount. This paper presents experimental evidence from high-speed photography of Charpy tests that the differences between dial/encoder energies and instrumented striker energies (measured with U-hammers) can largely be explained by post-fracture collisions with the striker. Further, experimental and numerical studies show that dynamic elastic deformations of the pendulum and striker, as well as load-cell errors due the distribution of the contact load and inertial effects, can also significantly contribute to the energy differences for some test-machine designs.

Experimental evidence from the literature that was originally expected to show the significance of residual vibrational energy in the test machine may actually show that low-energy Charpy specimen behavior can be significantly affected by the design of the test machine. A simple dynamic model of a specimen and test machine system shows that a 20% increase in the stiffness of the striker and hammer assembly can lead to a 9% decrease in the energy required to fracture a low-energy Charpy specimen.

KEYWORDS: Charpy, instrumented impact test, absorbed energy, encoder, vibration.

PENDULUM RESIDUAL VIBRATION ENERGY

Although dynamic test machine pendulums and their support structures are designed to be as rigid as practical, they can never be perfectly rigid. This means that an impulse load applied to the pendulum will result in elastic deformations in the machine components, which include both strain and kinetic energy (vibrational energy). The ultimate source of the pendulum's vibrational energy is the initial potential energy of the pendulum and therefore the energy that is indicated by the machine's energy dial, or inferred from an optical encoder, includes any pendulum vibrational energy. Energies computed by integration of striker load-cell forces do not include vibrational energy left in the pendulum since the integration of the force-deflection data provides the work done on the specimen over the few milliseconds required for the specimen to undergo fracture.

Finite-element simulations of a previous study calculated how much energy is left in the pendulum of a 400 J U-hammer Charpy test machine in the form of residual vibrational energy [1]. Simulated strike positions included the nominal center of percussion (CP), 1% above the CP, and 0.57% below the CP. Calculated residual vibrational energies in the pendulum were in the range of 0.07 to 2.9 J. It was concluded that pendulum residual vibrational energy is a significant factor in observed dial/encoder versus striker energy differences. In the present study, the magnitudes of the vibrational energy were confirmed experimentally for strikes very near the center of percussion. The approach was to mount accelerometers at various locations on the pendulum and hammer. Accelerations were recorded during tests using National Institute of Standards & Technology (NIST) verification specimens (low-energy specimens ~16 J, high-energy specimens ~101 J, and super-high-energy specimens ~217 J). Converting the acceleration data into vibrational energy involved calculating the fundamental vibration modes of the pendulum and developing analytical models relating accelerations, strain energy, and kinetic energy for each mode. The accelerometer data was subjected to a Fourier analysis so accelerations could be associated with each fundamental mode of vibration. The vibrational energy was then calculated for each mode and summed to get the total vibrational energy. The results of the vibrational energy experiments are summarized in Table 1. Estimated vibrational energies based on the tube lateral-vibration model ranged from 0.16 J to 0.47 J. The higher-energy Charpy tests resulted in larger vibrational energy. Computed vibrational energy was between 0.2% and 0.7% of the measured Charpy energy with the larger percentages of vibrational energy being for the lower-energy specimens. Vibrational energy estimates based on the U-hammer angular-vibrations were nearly identical to those from the lateral-vibration model for the lowest energy Charpy specimen. For the higher energy specimens, the energy estimates were somewhat higher than from the lateral-vibration model (0.95 and 2.20 J). For the U-hammer machine of this study, it appears that vibrational energies approach, but do not exceed, 1% of the Charpy energy. The vibrational energy for the high and super-high-energy specimens was primarily contained in the lowest frequency fundamental vibration mode (136 Hz). The low-energy specimen contained the most energy in the third or fourth fundamental mode (1224 or 2175 Hz).

Table 1 Summary of pendulum vibrational energy estimates from analysis of pendulum acceleration data.

Specimen Type	**Charpy Energy (J)**	**Vibrational Energy (J)**	**Vibrational Energy (%)**	**Peak Energy Frequency (cps)**
Tube Lateral-Vibration Model				
Super high energy	227.7	0.47	0.2	136
high energy	131.9	0.35	0.3	136
low energy	23.0	0.16	0.7	1224
Hammer Angular-Vibration Model				
Super high energy	211.8	2.02	1.0	136
high energy	131.0	0.95	0.7	136
low energy	22.3	0.15	0.7	2175

ENERGY ASSOCIATED WITH POST-FRACTURE IMPACTS

Instrumented striker measurements were made on a U-hammer test machine at NIST simultaneously with high-speed videos. Over 50 high-speed videos of the impact event and subsequent interaction with the striker were recorded at 3000 frames per second. The camera was positioned in front or behind the test machine so that the specimen/striker interaction could be viewed from both perspectives. Standard Reference Materials (SRMs) 2092 (low-energy range of 12 – 20 J), 2096 (high-energy range of 88 – 115 J), and 2098 (super-high-energy range of 210 – 224 J) were tested. The focus of this investigation was on characterizing the post-fracture interaction between the specimen and the striker so that the energy associated with post-fracture impact of the specimen halves with the striker could be quantified.

Depending on the test conditions, specimens left either through the back of the test machine (opposite the striker direction) or the front (direction of striker motion). Five categories of post-impact behavior were observed, determined by the material and test temperature:

1. Specimen halves initially move normal to the crack plane (away from the striker) and exit the rear of the test machine without striker interaction.
2. Specimen halves undergo rotation, impact the anvils, and leave through the rear of the test machine without striker interaction.
3. Specimen halves undergo rotation, hit the rear of the striker, and either leave through the rear or fall down on the support pedestal.
4. Connected or unconnected specimen halves leave through the front of the test machine, after one or more post-fracture impacts with the striker.
5. Connected or unconnected specimen halves leave through the front of the test machine without interaction with the striker.

During the first round of tests, a qualitative correlation between the number of post-fracture hits and the energy difference between the encoder and instrumented striker energies was observed. In all of the low-energy range tests, the instrumented striker energy was less than the dial energy and this difference was observed to be larger in cases where there were multiple post-fracture impacts with the striker. The best agreement in energy (typically within about 1%) was obtained for the higher energy tests where the specimen left through the front of the test machine still connected and without any striker interaction. Good agreement was also obtained for low-energy specimens where the broken halves leave through the rear of the test machine without contacting the striker. The largest differences occurred when the broken test specimens rebounded off the anvils and/or the test machine exit channel (characteristic of U-hammer test machines) and hit the striker. There were many cases where the test specimen rebounded several times off the exit channel and striker. It is interesting to note that the exit channel, which was constructed from low-strength carbon steel on this machine, has indentation marks from specimen interaction. The accumulation of these indentations can be detrimental because they can facilitate exit channel/striker interactions.

Two more sets of tests were performed to quantify the magnitude of the energy difference. The first set of tests was conducted at 20 °C using an alloy which is capable of complete fracture and whose specimens leave the machine by both the front and rear. The tests conducted at 20 °C strongly favored leaving by the front. The few specimens leaving by the rear either had no interaction with the striker or at most had one minor glancing-type contact where a rebound from the striker was not apparent. All of the specimens leaving by the front had numerous rebounding-type impacts with the striker. These data show that the post-fracture impacts with the striker associated with specimens that left by the front add an average of 2.9 J to the dial energy (2.3 J standard deviation). Additional tests were then conducted with the same material at –40 °C to obtain a higher percentage of specimens leaving by the rear, with the results are shown in Table 2. These experiments gave a slightly higher post-fracture striker interaction energy of 4.6 J (3.3 J standard deviation). Overall, these experiments show that post-fracture specimen-striker interactions can account for a large share of the energy difference between the dial and the instrumented striker energies.

Table 2 **Optical encoder energy results for impact tests conducted with simultaneous high-speed photography. Tests conducted at -40 °C.**

Specimen Left by the Rear of Test Machine			Specimen Left by the Front of Test Machine		
ID LL1-	**Energy (J)**	**Striker Contact**	**ID LL1-**	**Energy (J)**	**Striker Contact**
250	16.2	No	73	19.7	Yes
252	15.5	No	126	18.2	Yes
182	17.2	No	15	21.3	Yes
242	18.9	1 hit	240	23.3	Yes
63	18.2	No	222	27.0	Yes
-	-	-	119	18.5	Yes
-	-	-	39	24.6	Yes
Average	17.2	-	Average	21.8	-
Std. Dev.	1.4	-	Std. Dev.	3.3	-

EXPERIMENTAL STUDIES FROM THE LITERATURE

ASTM Instrumented/Miniaturized Round Robin Test Program

Results from a round-robin test program (to compare Charpy energy test results obtained by different laboratories) were compiled and reported by Manahan et. al. [2]. Standard Charpy V-notch (CVN) and miniature (half-scale) Charpy V-notch specimens (MCVN) were included in the study. Instrumented strikers were used to obtain load vs. time records and key loads were reported along with striker-based energies as well as dial/encoder energies. The round robin used material from a previously characterized A533B Class 1 plate and two varieties of 4340 steel prepared by NIST using methods similar to those used to prepare specimens for certifying Charpy test machines. The results of this ASTM round robin were examined as part of the current study to see if there was a statistically significant difference between the reported instrumented striker energies and the dial/encoder energies. As described above, differences could be due to residual vibrational energy in the pendulum, to load errors due to contact force distributions being different in the test from those during calibration, or to other unknown causes.

Comparing the dial/encoder energies to the instrumented striker energies revealed that, for CVN tests above 40 J, the energy agreement was within ± 5%. For CVNs with energy below 40 J, the agreement was within ± 18%. The MCVNs all had energies below 40 J and were in agreement to within ± 12%. Since there were six duplicate tests for each material/temperature/lab combination, it was possible to get a sense of how much of the difference between the two measures of energy was due to random effects. Comparing the differences of the averaged values (6 tests) only tightened the above three levels of agreement to 3 %, 15 %, and 10 %. This suggests that the differences in the reported energies are systematic rather than random.

A paired-t test was used to determine the statistical significance of the observed differences between encoder/dial and instrumented striker energies. Each value is based on the average differences from six duplicate tests by the same laboratory. For 9 out of 19 material/temperature/lab CVN data sets, the average energy difference was large enough (compared to the standard deviation of the differences) to conclude with 99% confidence that there is a systematic difference between the average measured dial energy and the average striker based energy. Lowering the confidence level to 95 % results in 15 of the 19 CVN data sets being consistent with there being systematic differences. For 14 out of the 16 MCVN data sets, it can be concluded with 99 % confidence that there is a systematic difference between the measured dial energy and the striker force based energy.

It is very clear from this comparison of dial/encoder and instrumented striker energies that there are significant systematic differences. There appears to be some bias in the less than 40 J range towards the instrumented striker energy being less than the dial/encoder energy. This is consistent with there being some residual vibrational energy included in the dial/encoder energies or that additional energy is removed from the pendulum by post-fracture interactions between the specimen and the striker. The significantly larger differences for the MCVN tests could perhaps be the result of their being tested on the lower-energy capacity machines. These machines could possibly be more prone to residual vibrational energy effects than larger capacity machines. Assuming that the load-cell strain gages for MCVN testing were placed on the striker similarly to those in the CVN testing, it would be expected that the load distribution effects would be smaller in the MCVN tests due to the smaller contact region (half). Striker load-cell inertial effects would not be expected to be the cause of the large energy differences due to the upper-shelf behavior (high plasticity) making the specimen behavior largely quasi-static. However, effect of test machine inertial/dynamics on the displacement histories computed from the striker load histories could be greater for the lower capacity and perhaps relatively less stiff MCVN test machines.

International Comparison of Impact Verification Programs

The keys to achieving reproducible test machine and laboratory independent dynamic test results have been adequate attention to testing machine design and maintenance and strict adherence to standard test procedures. The means for ensuring that various Charpy test laboratories can generate laboratory independent test results are the four international Charpy machine certification programs (described by McCowan et. al. [3]). The reference [3] study is a round robin conducted by the four Charpy certification laboratories. Our original interest in studying these data was rooted in examining the striker encoder/instrumented energy differences. However, as will be discussed, a very interesting finding was made as a result of this study.

Each of the four participants provided three energy levels of calibration specimens for the study, so that there were 12 different specimen groups. Each participant received 25 specimens from each specimen group. Each participant tested 15 of each group using a 2 mm striker and the remaining 10 with an 8 mm striker. The certified energy levels ranged from 16.5 J to 258 J. Participant 4 did not provide certified values for their specimens due to there being too few specimens to apply their standard certification procedure and still provide specimens to the round robin. It was not explicitly stated by McCowan et. al. in their conclusions, but each participant was able to pass the certification standards for each specimen and striker combination for which certified values were determined. By drawing this conclusion, the ISO 148-3 requirements could be applied to the specimens of participants 1 and 2, and ASTM requirements were applied to the specimens of participant 3. Since participant 4's specimens did not have certified values, their specimens were not considered in making this conclusion. If participant 4's average round robin test values for its own specimen groups were treated as the certified values, the conclusion would still be that all passed. Interestingly, if the tighter ASTM tolerances at low energies (± 1.4 J or 1 ft-lb) were substituted for the ISO requirements (± 2 J), two participants would have failed to match the certified values to within required limits on some low-energy specimen groups. With the ASTM limits, participant 4's energies would have been too low on all three certified specimen/striker combinations of the low-energy specimen groups 1 and 2 (-1.5 to -1.8 J vs. the specified ± 1.4 J limit). Participant 3's energy would have been too high (1.5 J vs. the ± 1.4 J limit) on the low-energy specimen group 1.

NIST records on certification failures show that the low-energy specimens are statistically the most likely to cause a test machine to fail meeting the certification requirements. The combined results for all data-years shows a failure rate of 12.0 % for the low-energy test, 8.6 % for the high-energy test, and 9.7 % for the super-high-energy test. It is interesting to note that the low-energy test shows the largest difference between C-hammer and U-hammer test machines, with the U-hammer test machines recording higher energies on average. However, the difference between the medians is only about 0.2 J. This value is lower than expected because C-hammer test machines experience less post-fracture test specimen/striker interaction. It is believed that the small difference in the medians is due to the fact that the majority of low-energy test specimens exit the rear of the test machine, which would tend to result in closer agreement between C and U hammers. The NIST records also show that failures at the low-energy level are more often due to measuring energies that are too high relative to the certified value.

Participant 4's tendency to obtain energies below the certified value is counter to this trend. The information provided by McCowan et. al. [3] shows that Participant 4 used a 500 J capacity test machine while the rest of the participants used 300 to 350 J machines. It was speculated that the use of the higher energy capacity machine was the root cause of the lower measured energies for the low-energy specimens. The basis for this conjecture was the assumption that the higher capacity machine, due to its larger mass and stiffness, experiences less residual vibrational energy in the machine than the lower capacity machines.

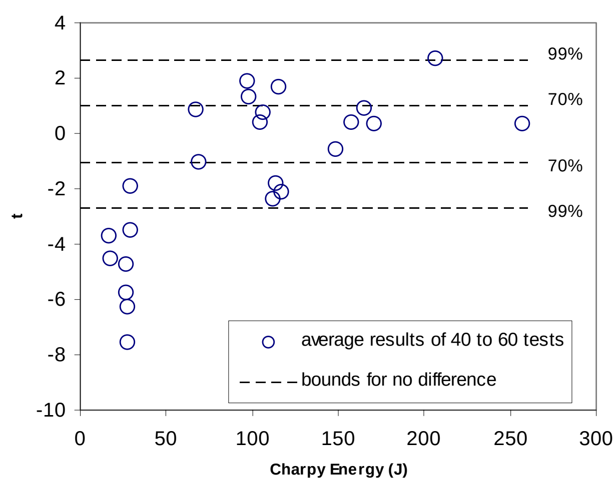

Fig. 1 Test statistic t for measured energy differences between the 500 J capacity machine and the average energies from the 300 to 350 J capacity machines.

The data from McCowan et al. was subjected to a statistical analysis to determine the statistical significance of the above noted differences in energy measured by the 500 J machine of Participant 4, relative to the 300/350 J machines of participants 1, 2, and 3. The large number of duplicate test specimens used in this study, combined with the small coefficient of variation of the specially-manufactured calibration test specimens, makes the data from this study ideal for identifying and studying effects that are normally lost in the scatter due to small data sets and the inherent variability of Charpy test results. The fact that the data is obtained from perhaps the best maintained testing machines in the world should also not be overlooked. The average results from Participants 1, 2, and 3 were used as the basis for comparison with Participant 4's results. Means (E_{123}) and standard deviations (s_{123}) were computed for the combined data of participants 1, 2, and 3. Similarly, means (E_4) and standard deviations (s_4) were computed for Participant 4's test results. Then, for each test, the difference in the mean values (E_4 – E_{123}) and a pooled standard deviation (s_0) were computed. Fig. 1 shows test statistic t as a function of the energy level for the 24 data sets. Keep in mind that each point represents 60 Charpy tests with a 2 mm striker or 40 tests with an 8 mm striker, and the t test is applied to each of the 24 points (e.g., not to the mean trend of the combined 24 data sets). The statistical significance of the normalized energy differences (t) is determined by comparing to the expected statistical distribution of t if there was no effect of machine capacity on the measured energies (assumes normal distribution and random sampling). The horizontal dashed lines show the expected ranges of t for 70 % and 99 % of the t population if there is no energy difference. For Charpy energies above 40 J, it can be seen that the computed t values are reasonably consistent with the hypothesis that there is no machine capacity dependence. Below 40 J, the t values are significantly below the expected range and it is concluded that there is a very significant difference in the energies measured by the 500 J machine at low Charpy energy levels.

This statistical test has therefore shown that the –2 % to –9 % energy difference (average –6.2 %) of the 500 J machine in the lower Charpy energy regime is not due to random effects. It was originally postulated that this systematic effect was due to residual vibrational energy. However, the accelerometer experiments described above and the numerical simulations of [1] could only explain differences of 1 to 2 %. Calculations performed in this study using a simple two mass-two spring model of the specimen and striker system suggests that the energy difference can be explained in terms of a frequency shift in the applied load caused by a stiffer striker/hammer design in the 500 J machine. The frequency at which the specimen and striker vibrate during the initial elastic loading is affected by the specimen's stiffness (k_s) and mass (m_s) as well as the stiffness of the hammer assembly (k_h) according to $f = (1/2\pi)\sqrt{(k_s + k_h)/m_s}$. The mass of the hammer (m_h) is essentially infinite with respect to that of the specimen and therefore does not affect the frequency behavior of interest. As shown in Fig. 2, a 20 % higher striker/hammer stiffness results in a 7 % increase in the natural frequency of the specimen/striker/hammer system. The higher frequency results in the critical fracture load being reached at a smaller specimen displacement, which in turn, results in less absorbed energy to fracture the specimen. These findings not only suggest that the observed low-energy measurements could be the result of the test machine design, but more importantly, that the test machine could be interacting with the specimen to materially affect the fracture behavior of the specimen.

SUMMARY

Numerical simulations and experimentation have demonstrated the potential for significant residual vibrational energy losses in Charpy test machines. For the 400 J U-hammer machine considered in this study, the estimated vibrational energy is on the order of 1 % of the Charpy test energy. While the vibrational energy is significant, it is not sufficient to explain the differences in dial and instrumented energies observed when testing low-energy specimens which exit the front of the test machine (on the order of 2 % to 20 %). These larger differences can be explained by the observed post-fracture striker/specimen interaction. Measurements performed during the current study showed that the post-fracture impacts with the striker add an average of 3 to 4.5 J to the dial energy. Thus, the post-fracture specimen-striker interactions can account for a large share of the observed energy differences between the dial and the instrumented striker energies. Other effects which add to the energy difference include: load-cell load distribution effects; test machine inertial effects, striker inertial effects; and windage/friction correction of the dial.

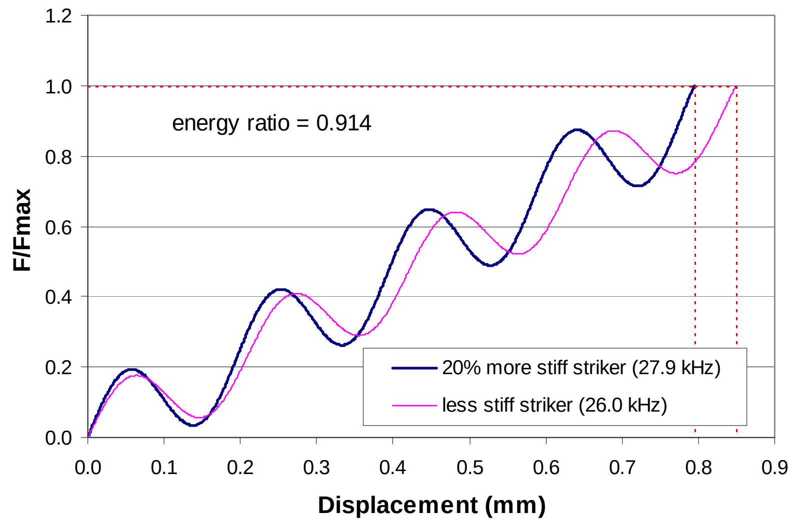

Fig. 2 Results of two mass-two spring model calculations to determine the effect of stiffening the pendulum on the absorbed energy measurement.

For the low-energy specimens of the international round robin reported by McCowan et. al. [3], the 500 J capacity machine gave energies that were 2 to 9 % less than those measured using 300 to 350 J machines. It was originally postulated that this systematic effect was mostly due to residual vibrational energy n the test machine. However, experimental and numerical studies on test machine vibrational energy have been unable to explain more than a 1 to 2 % difference. The simple two mass-two spring dynamic model of this study has shown that a 20 % change in striker/hammer stiffness can lead to an absorbed energy difference of about 9 % in low-energy Charpy specimens. Therefore, it now appears that the observed 2 to 9 % energy difference could be due to a stiffer striker/hammer design for the 500 J machine. The mechanism for this energy difference is that increasing the striker/hammer stiffness increases the frequency of the inertial peaks during the elastic portion of the specimen response. This higher frequency results in the critical fracture load being reached at a smaller displacement, which in turn, results in lower absorbed energy before fracture. These findings are potentially important because they suggest that the energy to fracture low-energy specimens is significantly a function of the test machine design.

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